Factors Influencing Silage Quality and Their Implications for Management

ABSTRACT

Preservation of crop quality, DM, and energy in the silo requires that plant respiration, plant proteolytic activity, clostridial activity, and aerobic microbial growth be limited. A critical mechanism for limiting these processes is quick attainment and maintenance of anaerobic conditions in the silo. If the crop is wilted to greater than 55% DM, fermentation of the crop plays a minor role in making quality silage. For wetter crops, a rapid decline in pH is essential.

Dropping pH by fermentation requires an anaerobic environment, adequate substrate, and sufficient numbers of lactic acid bacteria. The substrate required for good fermentation is dependent on the crop, increasing with buffering capacity and moisture content. Approximately $10^8$ lactic acid bacteria per gram of crop are required before a noticeable drop in pH occurs. Because this concentration is much greater than that supplied by inoculants, the most important characteristic for an inoculant is fast growth rate in the silo environment. Also, an inoculant's success depends on adequate substrate and its population relative to the natural one. Dropping pH by acids effects an immediate pH change, which is beneficial in preserving protein nitrogen. However, this advantage must be balanced against its cost and safety in handling.

INTRODUCTION

There are several methods of storing a crop until it is ready to be used or sold. A crop may be dried to the point at which biological activity is essentially nil, such as with hay or dry shell corn. Alternatively, a crop may be stored directly or with minimal drying by maintaining the crop under anaerobic conditions in a silo. In this storage system, preservation is accomplished by both the anaerobic environment and a bacterial fermentation of sugars, which lowers pH primarily through the production of lactic and acetic acids.

The goals of either storage system are the same. First, the quality or feeding characteristics of the crop removed from storage should be very similar to that which entered storage. Ideally, any changes in the composition of the crop during storage should not adversely affect any aspect of the crop's use. Second, DM and energy losses should be minimized. There may be negligible changes in crop quality during storage based on fiber and CP concentration, but significant losses of DM may occur that have a substantial impact on a farm's profitability.

The ensuing discussion will focus on the ensiling of forage crops and whole-plant corn. Many of the principles apply to ensiling of other crops as well, but not necessarily. Also, effluent production is not addressed in this discussion. Wilting or allowing the standing crop to naturally dry down is a standard practice in the US to prevent substantial DM and energy losses in effluent. For the purposes of this discussion, crops are assumed to be wilted such that effluent losses are not a problem.

BIOLOGICAL PROCESSES ADVERSELY AFFECTING ENSILING

Four main types of biological processes may negatively affect the ensiling of a crop: plant
respiration, plant enzyme activity, clostridial activity, and aerobic microbial activity. Each is discussed briefly.

**Plant Respiration**

The crop entering a silo continues to respire, using oxygen and sugars and producing carbon dioxide, water, and heat. This process eliminates oxygen from the silo, creating an anaerobic environment for silage fermentation and, consequently, serving a useful purpose.

The unavoidable loss of DM and sugars to remove oxygen trapped in the silo at sealing is minimal (21). For example, the uncompacted wet density of corn or alfalfa silage is approximately 400 kg/m³, and the air to herbage volumetric ratio is approximately 2:1 for 40% DM herbage (40). Assuming that the air is 21% oxygen and that glucose is respired, only .12% of the herbage DM would be lost removing the trapped oxygen. If sugar content were 3% DM (a low value for forages; (21)), this loss would represent 3.9% of the sugar. Thus, losses resulting from oxygen trapped at the sealing of a silo are not significant.

If a silo is filled slowly or imperfectly sealed, excessive respiration may occur, resulting in potential problems. First, respiration causes loss of DM. Second, the DM that is lost is rapidly fermentable carbohydrate (21). This represents a loss in the energy value of the crop as well as substrate for lactic acid fermentation. For forage crops like alfalfa, the loss of sugar may severely limit preservation (44, 57). Third, prolonged respiration delays the onset of pH decline and allows detrimental plant and microbial activity to continue (17, 18, 38, 44). Finally, respiration produces heat that may increase the formation of Maillard products, including acid-detergent insoluble N (48).

**Plant Enzyme Activity**

The enzymes involved in respiration are not the only ones remaining active as the crop is ensiled. Significant hydrolysis of starch and hemicellulose to monosaccharides occurs. For each polysaccharide, the amount may be upwards of 1% DM or more with forages (9, 25). Hydrolysis of such compounds provides additional sugars for lactic acid fermentation. The reduction in hemicellulose also lowers NDF concentration; however, the same amount of indigestible fiber most likely remains.

In contrast, proteolytic enzymes can lower the feeding value of an ensiled crop. These enzymes convert protein N to nonprotein nitrogen (NPN) forms such as peptides and free amino acids, whereas further reduction to ammonia and amines is largely caused by microbial activity (34). In alfalfa, ensiling can result in up to 85% of the total N being NPN (26). When extensive proteolysis occurs, a farmer may have to purchase additional protein supplements based on the latest NRC recommendations (31) to get optimum milk production from his cows even though the total CP of the diet appears adequate. Thus, proteolysis in making silage could seriously affect the cost of producing milk.

**Clostridial Activity**

Clostridia are the principal anaerobic microorganisms detrimental to silage quality. There are two main groups of clostridia: saccharolytic and proteolytic. The saccharolytic clostridia chiefly ferment carbohydrates and organic acids producing butyric acid, carbon dioxide, and hydrogen. Proteolytic clostridia primarily ferment amino acids, resulting in a variety of organic acids, carbon dioxide, ammonia, and amines (21). These fermentations result in both DM and energy losses, but the primary cause of concern is the production of butyric acid, ammonia, and amines, which have been linked with reduced ad libitum feed intake in ruminants (8, 32, 33, 52).

**Aerobic Microbial Activity**

Air seeping into the silo through imperfect sealing or upon opening for feed out allows aerobic microorganisms to grow and can cause extensive deterioration of silage. Fungi, particularly yeasts, are the microorganisms most often associated with this activity; however, bacteria (primarily *Bacillus* species) have also been implicated (55). These organisms use a wide range of substrates, but rapidly degradable carbohydrates, organic acids, and proteins are the most important (55). The carbohydrates and organic acids are respired resulting in the loss of DM and energy plus the production of heat. If heating at feedout raises silage temperatures to 60°C, aerobic microbial activity
could accelerate formation of Maillard products (12). As with plant proteolysis and clostridial activity, microbial proteolytic enzymes can deleteriously affect the feeding value of the nitrogen in silage, producing mostly ammonia (55). Finally, growth of certain molds (e.g., certain species of Fusarium and Aspergillus) on silages can produce mycotoxins, which are harmful to cattle (21).

Summary of Biological Processes

All four processes may affect silage feed quality, but the principal factors reducing quality are plant proteolytic enzymes, clostridia, and aerobic microorganisms. In contrast, only three processes are responsible for DM and energy losses: plant respiration, aerobic microorganisms, and clostridia. Of these, the first two are generally the most important.

MECHANISMS TO MINIMIZE LOSSES OF DRY MATTER, ENERGY, AND QUALITY

Plant Respiration

Because respiration requires oxygen, quickly attaining and then maintaining an anaerobic environment alleviates excessive plant respiration. It has long been recognized that silos should be filled quickly (21), making sure that there are no cracks in the silo for air infiltration and sealing the top of silo with plastic. Studies by Wood (54) also indicate that the drier the crop being ensiled the greater the DM filling rate necessary to prevent excessive heating from respiration. The practical upper limit on DM content to prevent substantial heating on most farms, based on his results, would be approximately 50% for tower silos. The critical DM content for bunker silos should be lower because of the greater exposed surface during filling compared with that for tower silos. If these recommendations were followed, the crop would be exposed to air for a minimal time between harvest and feed out. Under such conditions, DM losses due to respiration are minimized.

Plant Proteolytic Activity

The activity of plant proteases in ensiled herbage is affected by four main factors: pH, time, DM content of the herbage, and temperature. The effects of pH on plant proteases have been studied primarily in legumes. Studies with white clover, red clover, alfalfa, and birdsfoot trefoil have generally reported pH optima around 6.0 with activity declining linearly with pH between pH 4 and 6 (4, 10, 23). At pH 4, however, the protease activity was still 15 to 35% of that at 6. Consequently, reducing the pH to 4 significantly reduces proteolytic activity but does not eliminate it.

Proteolytic activity decreases with time during fermentation in the silo. For both whole plant corn (2) and alfalfa (24, 26), the greatest proteolysis occurs during the 1st d in the silo, declining to little proteolysis after 5 d of fermentation. The decline in proteolysis rate with time is independent of DM content in alfalfa (26). Thus, measures to reduce proteolysis must be effective upon ensiling or shortly thereafter.

Dry matter content also is a significant factor affecting plant proteases. For alfalfa, Muck (26) found that proteolysis rate was negatively and linearly correlated with the DM content of the herbage and that little proteolysis occurs above 75% DM. The total amount of proteolysis for DM less than 50% was not closely correlated with DM content (Figure 1). The reason for this is that DM also influences the growth of lactic acid bacteria and thus the pH time course. For wetter silages (<50% DM), pH usually drops within the first 5 d in the silo, so interaction between initial
numbers of lactic acid bacteria and DM content on pH time course may cause a large variation in the amount of proteolysis (26, 29). With drier silages, particularly above 60% DM, the drop in silage pH does not happen until most proteolysis has occurred (26, 29). Consequently, the effect of DM on the amount of proteolysis is more consistent among high DM silages.

Finally, increasing temperature over the range of 10 to 40°C increases proteolysis rate (4, 10, 22). However, like DM, temperature also affects the rate of fermentation and, thus, pH time course. Experiments with alfalfa ensiled at different temperatures indicated a consistent 10 unit increase in NPN expressed as a percentage of total N for temperatures between 15 and 35°C (28). Although it is not always possible to control the temperature of the crop entering the silo, it is possible to prevent further heating caused by slow filling or poor sealing.

Consequently, for wetter silages (<50% DM), decreasing silage pH rapidly and maintaining low silage temperature appear to be the most appropriate strategies for reducing proteolysis. Heavily wilting the crop (60% DM or greater) is an alternative, but the increased potential for field losses prior to ensiling (16) and for heating in the silo (40) may offset the benefits of this strategy.

**Clostridial Activity**

The pH at which clostridial activity ceases is dependent on water activity (50), which is related to the DM content of the herbage (13). Using the mathematical relationships developed by Leibensperger and Pitt (19) from the data of Wieringa (50) and Greenhill (13), the pH at which the activity of *Clostridium tyrobutyricum* stops as a function of DM is shown in Figure 2 for legumes and ryegrass. The relationship with other clostridia may vary from this, but *C. tyrobutyricum* is one of the important species found in silages (11), and the curve for ryegrass agrees well with the results of Wieringa (51) for grass silages. Consequently, unwilted silages may require pH in the low 4's to completely inhibit clostridial activity, and the wilting required to completely assure inhibition of activity is approximately 40 to 50% DM, depending on the crop.

![Figure 2. The pH at which the growth of *Clostridium tyrobutyricum* ceases as a function of the DM content of the crop. Based on the equations reported by Leibensperger and Pitt (19) developed from the data of Wieringa (50) and Greenhill (13).](image-url)
activity contained enough butyric acid to make them aerobically stable. A recent study of legume silages (39) indicated that a product of fermentation (as yet undetermined but not butyric acid) made them aerobically stable. Aerobic stability in nonclostridial silages appears linked with fermentation but not in a manner that is obvious or predictable at this point.

Various additives have been proposed or used to stop or reduce aerobic microbial activity. Propionic acid and higher molecular weight VFA have been used effectively (47, 55, 58). With silages like corn, which are low in CP, the addition of ammonia or urea at ensiling can be effective in improving aerobic stability by inhibiting fungal growth (5). Finally, antimycotic agents like pimaricin have been used effectively (56). With these treatments, cost is a primary factor in the failure of their adoption. The most likely candidates economically are propionic acid and ammonia. In any case, maintaining an anaerobic environment is the cheapest and most efficient means of reducing this problem.

**IMPLICATIONS FOR MANAGEMENT**

Three major implications for silage management can be derived from the foregoing discussion of the biological processes, which adversely affect ensiling, and the mechanisms to minimize them. First, quickly creating and maintaining an anaerobic environment in the silo is a critical factor in producing high quality silage and avoiding the negative impacts of plant respiration, plant proteolysis, and aerobic microbial activity. Respiration, both plant and microbial, requires oxygen, so there is a direct link between cessation of respiration and attainment of anaerobic conditions. The link between plant proteolysis and anaerobic conditions is less direct. Proteolysis is reduced by maintaining a low temperature (28) and by rapidly decreasing pH (2, 4, 10, 23, 24, 26). In contrast, slow filling or imperfect sealing would allow additional respiration, increasing silage temperature. Also, delays in sealing postpone the onset of pH decline (18, 38, 44, 57). Therefore, poor silo management at filling would increase proteolysis.

A second implication for management is that fermentation (or decreasing pH) is relatively unimportant in producing high quality dry (>55% DM) silages. At these DM contents, clostridial activity is totally inhibited (19, 50, 51), and proteolysis is substantially reduced by the low water activity (26). Generally, the decrease in pH caused by fermentation comes too late (>5 d of fermentation) to be of any use in reducing proteolysis (26). Consequently, fermentation does little to improve silage quality under these conditions.

This does not mean that high DM silages are necessarily desirable. Harvesting drier crops will typically incur greater weather risk as well as larger harvesting losses (16). Another problem is that drier crops do not pack adequately, they have a lower specific heat, and they are more porous (40). The combination of these factors means that drier silages are more susceptible to heating and aerobic losses from either plant respiration or aerobic microbial activity (41).

A final implication is that a rapid pH decline is important in making high quality silages when the DM content is 50% or less. Reducing both plant proteolysis and clostridial activity under these conditions essentially requires that pH be decreased as soon as possible after ensiling (19, 26). Final pH after fermentation is of some importance in assuring no clostridial growth. However, a low final pH is not a guarantee that clostridial activity was prevented or that proteolysis was minimized. These can only be guaranteed by a rapid attainment of a low pH.

**MECHANISMS FOR DECREASING pH**

Because many crops are ensiled under wet conditions (<50% DM), mechanisms for rapidly decreasing pH need to be discussed. Normally this is accomplished by the fermentation of sugars by lactic acid bacteria naturally present on the crop. However, as can be seen in the following discussion, this fermentation may be assisted by inoculation with selected strains of lactic acid bacteria, by addition of acids to the crop as it is put in the silo, or by addition of sugars when endogenous amounts in the crop are low.

**Fermentation**

A successful lactic acid fermentation requires three elements: an anaerobic environment, adequate substrate for the lactic acid
bacteria, and a sufficient population of lactic acid bacteria.

Lactic acid bacteria actually includes bacteria from a number of genera (Lactobacillus, Pediococcus, Leuconostoc, and Streptococcus), which produce lactic acid as the principal product of fermentation (21). These bacteria can grow aerobically but prefer to grow under anaerobic conditions (6). Under aerobic conditions, they produce some lactic and acetic acids; however, considerable substrate is respired to carbon dioxide and water (21). Consequently, anaerobic conditions are desired for efficient bacterial growth and conversion of substrate to acids.

Typically, the substrate for lactic acid bacteria is mono- or disaccharides. However, there are several other sources of substrate. Some lactic acid bacteria can ferment citric and malic acids, which are present in forage crops (21). Also, as indicated earlier, plant enzymes hydrolyze some starch and hemicellulose, providing additional hexoses and pentoses for fermentation. Thus, the measurement of sugars or even water soluble carbohydrates may underestimate substrate available for the lactic acid bacteria.

The amount of substrate necessary for a complete fermentation (i.e., one that is stopped by pH inhibition of bacterial growth) is dependent on two principal factors: buffering capacity and DM content of the crop. Buffering capacity as used here is the amount of acid required to drop crop pH from 6 to 4 per unit DM. Melvin (25) found that the final pH of unwilted alfalfa silage was negatively and linearly correlated to the sugar:buffering capacity ratio. In other words, to achieve the same final pH for two different alfalfa cuttings required sugar contents in the same relative ratio as their buffering capacities. Based on Melvin (25) and Muck and Walgenbach (30), high buffering capacities in alfalfa are associated with high potassium fertilization, with first cutting, and with immature alfalfa. Ensiling these types of alfalfa requires greater concentrations of sugar than either later cuttings or more mature alfalfa.

Dry matter content affects the amount of substrate required by affecting the pH at which lactic acid bacterial activity ceases. Data from Muck and Speckhard (29) (see Figure 3) show the effect of DM content on sugar requirements in two ways. First, pH of silages with sugar added varied substantially depending on the DM content. The driest silages had a much greater final pH indicating that less fermentation had occurred than in the wetter silages. Second, adding sugar to the silage had the largest effect with the wettest silage. Consequently, the substrate required for a complete fermentation is negatively correlated with the DM content of the crop.

The number of lactic acid bacteria on a crop prior to ensiling is highly variable. Measurements of lactic acid bacteria on standing crops of grasses, cereals and legumes have typically shown less than 10 cfu/g herbage (27, 46). Most of the bacteria found were associated with damaged or decaying plant material. With corn, increasing numbers with maturity have been reported, and average numbers were substantially greater than those on grasses and legumes (20).

With wilted grasses and legumes, the mowing operation tends to increase the number of bacteria on the forage (15, 27). Lactic acid bacteria counts on forage in the swath may increase during wilting when environmental conditions promote growth. However, little growth has been reported unless the average wilting temperature was at least 15°C (27). Growth also depends on the rate of drying and the length of wilting time. Bacterial numbers on alfalfa wilted in the swath for 24 h were generally less than 1000 cfu/g except when almost no drying occurred. With 48 h of wilting,
lactic acid bacterial numbers were negatively correlated with the DM content of the alfalfa (27). The slower the drying the greater the number of lactic acid bacteria observed. If the bacterial numbers on the swath were below 100 cfu/g, then the chopping operation apparently inoculated the forage at between 10^2 and 10^4 CFU/g. The amount of inoculation was correlated with air temperature at chopping and also appeared to be negatively correlated with DM content of the crop (27). Considering the combination of all factors under northern Midwest conditions, the average numbers of lactic acid bacteria on chopped alfalfa entering the silo is approximately 10^3 to 10^4 cfu/g with a range of 10^2 to 10^8 cfu (27).

The number of lactic acid bacteria required for an immediate decrease in pH is approximately 10^5 cfu/g, as is indicated in Figure 4 using a simulation from the model of Pitt et al. (42) modified as per Leibensperger and Pitt (19) and Muck (26). The numbers applied by most inoculants (10^5 to 10^6 cfu/g) is substantially below this. This means that an inoculant will not decrease pH immediately. Assuming pure culture growth rates, the model of Pitt et al. (42) predicts lags of 10 and 26 h for 30 and 55% DM alfalfa, respectively, inoculated at 10^5 cfu/g and ensiled at 30°C. Actual lags before the onset of pH decline might be somewhat longer due to less than ideal conditions; however, they might be less if the inoculant strains are much faster than the average natural ones.

This leads to the question of which characteristics are most important in an inoculant. Bacterial strains that produce mostly lactic acid (homofermenters) have been favored as inoculants, because lactic acid is a much stronger acid than other fermentation end-products of lactic acid bacteria and because the homofermentative pathway results in no DM losses (21). Homofermentativeness alone as shown in Figure 5 will not substantially speed the initiation of pH decline even though a lower final pH would be expected. An inoculant must grow faster than a natural population of the same number in order to effectively improve on the initiation of pH decline. Also, an inoculant is unlikely to dominate a natural population greater than it unless growth rate of the inoculant is substantially greater than that of the natural one.

The theoretical improvement of a homofermentative strain over the natural strains in terms of DM loss is small. Typically, the natural strains are a mix of hetero- and homofermentative strains (46). Even if the natural strains were all heterofermentative, a homofermentative inoculant could only make small differences in DM recovery. A strictly heterofermentative fermentation of glucose would produce one mole each of lactic acid, acetic acid, and carbon dioxide (21). The carbon

![Figure 4. Computer simulation of the fermentation of alfalfa, ensiled at 35% DM and 25°C and having a sugar content of 8% DM and buffering capacity of 400 meq/kg DM, using the model of Pitt et al. (42) with modifications as described by Muck (26).](image)

![Figure 5. Computer simulation of the pH of ensiled alfalfa using the same parameters as in Figure 4, except for varying the characteristics of the lactic acid bacteria involved in fermentation. The 1X homofermentative indicates that the lactic acid bacteria produced only lactate and had the same growth rate characteristics as the natural population. The 2X indicates a homofermentative population growing twice the rate of the natural one. All simulations started with lactic acid bacteria at 10^5 cfu/g alfalfa.](image)
dioxide represents approximately one-fourth of the weight of glucose. If glucose made up 8% of the DM of a crop and were all fermented heterofermentatively, that would represent a 2% loss of DM. However, the fermentation of fructose and pentoses heterofermentatively produce far smaller DM losses (21), and from data compiled by Pitt et al. (42), heterofermentation normally accounts for less than half of the end products in a natural silage fermentation. Consequently, the theoretical increase in DM recovery by use of an inoculant is probably on the order of 1 percentage unit based on fermentation end products and assuming that the inoculant does dominate the fermentation. This is similar to values reported by experimental use of inoculants (3).

Furthermore, heterofermentation does not necessarily result in energy losses equivalent to DM losses. For example, the homofermentative conversion of glucose to lactate results in a 0 and .7% loss of DM and energy, respectively, whereas the heterofermentative fermentation to lactate, ethanol, and carbon dioxide results in a 24.0 and 1.7% loss of DM and energy (21). Similar comparisons with other heterofermentative pathways and other substrates show similar results. Consequently, reducing this DM loss is less critical than reducing DM losses occurring from plant and microbial respiration, which result in substantial concomitant losses of DM and energy.

Based on these facts and assumptions, growth rate is the most important characteristic of an inoculant in order to decrease pH rapidly. Homofermentativeness is beneficial but to a lesser degree. Finally, in order for the inoculant to dominate the fermentation when its numbers are less than the natural population, the growth rate of the inocula must be substantially greater than that of the natural population.

### Addition of Acids

Acids are rarely used as silage additives in the United States, but they have been the principal type of additive in Europe. The two most common acids are formic and sulfuric. Acids immediately decrease the pH of the crop entering the silo and thus have an advantage over fermentation in reducing proteolysis. In Table 1, the proteolysis predicted for the simulations in Figure 5 are compared with the proteolysis from acidifying the alfalfa with formic acid to pH 4.75. The inoculants provided little benefit in reducing proteolysis compared with using formic acid. The acid, however, did not completely inhibit proteolysis. There is still substantial proteolytic activity at pH 4.75 plus the development of enough lactic acid bacteria to lower the pH further under these acid conditions is inhibited until proteolysis has essentially ceased.

The results in Table 1 are for conditions normally encountered in the US but an inoculant may inhibit proteolysis as well as an acid. Carpintero et al. (7) reported that an inoculum plus glucose treatment on an unwilted ryegrass-clover mixture performed almost as well as lowering pH to 4 with either formic or sulfuric acids in preventing proteolysis. In that experiment, the inoculum treatment was at pH 3.8 by d 4 whereas the pH of the acid treatments increased slightly. However, under typical US conditions, proteolysis in alfalfa was reduced by an inoculum an average of 4.4 to 7.5% as compared with the control, depending on DM content of the crop (45). The

### TABLE 1. Relative amount of proteolysis with computer-simulated (26, 42) alfalfa silage ensiled at 25°C with lactic acid bacteria (LAB) populations of $10^9$ cfu/g alfalfa. Homofermentative LAB simulate inoculants producing only lactate and growing at (1X) or double (2X) the rate of the natural population.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Relative proteolysis</th>
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<tbody>
<tr>
<td>Natural LAB</td>
<td>100.0</td>
</tr>
<tr>
<td>1X Homofermentative LAB</td>
<td>99.6</td>
</tr>
<tr>
<td>2X Homofermentative LAB</td>
<td>94.6</td>
</tr>
<tr>
<td>Formic acid to reduce pH to 4.75 at ensiling</td>
<td>63.7</td>
</tr>
</tbody>
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reduced extent of fermentation and the slower fermentation rate with drier silages will favor acids over inoculants.

A further improvement in both protein preservation and animal performance has been shown by applying formalin or formaldehyde to the crop in addition to formic or sulfuric acid (21). Formaldehyde, however, is not approved for use in the US.

Another advantage of acid to lower pH is that the amount of sugar or substrate for fermentation becomes unimportant. This assumes that sufficient acid is added to the crop based on the DM content and the sugar to buffering capacity ratio (49). An inoculant may be ineffective in preventing clostridial activity or reducing proteolysis if there is little substrate available. With an acid there is less uncertainty.

Disadvantages of acid include safety in handling and corrosion of equipment. Formic acid has typically been more expensive than inoculants in the European market; however, sulfuric is very competitive (53).

The great difficulty under US conditions is knowing when an additive is going to be beneficial. Continued research is necessary that emphasizes 1) the conditions under which an additive substantially improves silage quality and reduces DM and energy losses and 2) the amount of improvement in silage quality needed to increase animal performance. Only when these results are available will sound recommendations be possible.

CONCLUSION

The goal of ensiling is to maintain crop quality throughout storage with minimal DM and energy losses. Major obstacles to producing high quality silage are plant respiration, plant proteolytic activity, clostridial fermentation, and aerobic microbial activity. To overcome these obstacles, a critical management factor is creating and maintaining an anaerobic environment in the silo.

For heavily wilted crops (>55% DM), fermentation by lactic acid bacteria has a minor role in making high quality silage with low DM losses. However, field losses and susceptibility to heating and respiration losses make heavy wilting an undesirable practice.

For wetter crops, rapid pH decline (not necessarily a low final pH) is essential for high quality silage. Rapidly decreasing pH by fermentation requires an anaerobic environment, adequate substrate for the bacteria, and sufficient numbers of lactic acid bacteria. The amount of substrate required increases with the buffering capacity and moisture content of the crop. The decline in pH starts when there are approximately $10^8$ cfu of lactic acid bacteria/g forage.

The most important characteristic of an inoculant is fast growth rate. Even so, the success of any inoculant depends on adequate substrate and its population relative to the natural bacteria on the forage. For preserving protein N, acids have an advantage over inoculants under current US practices because acids immediately lower silage pH.

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